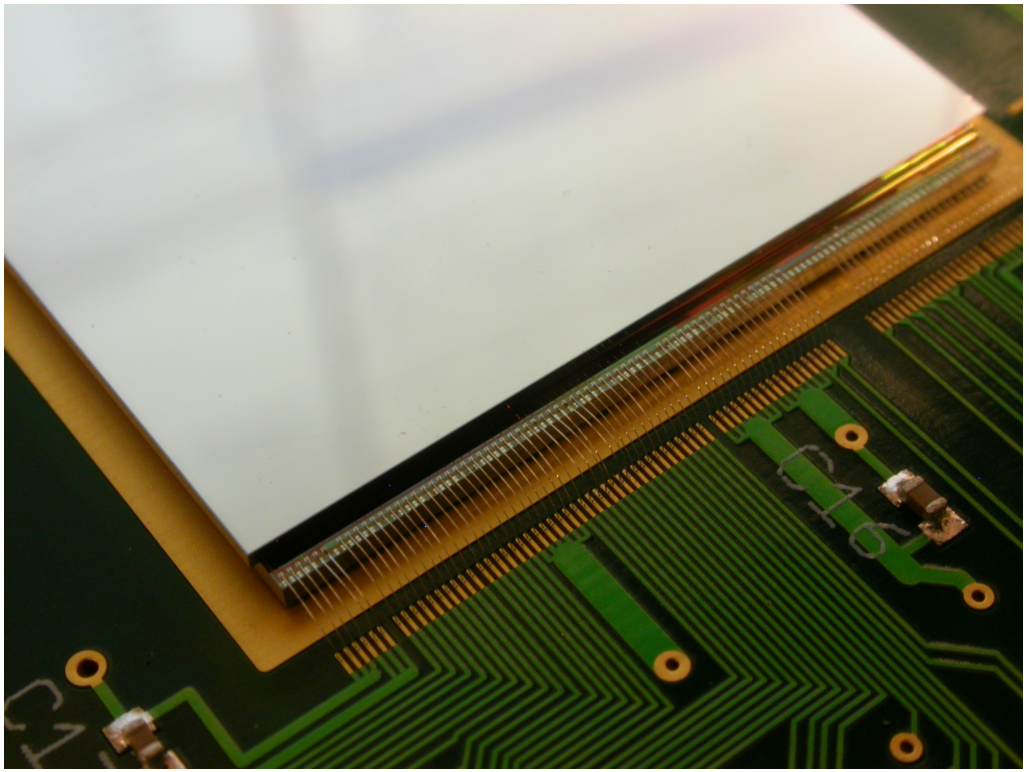
X-Ray Tests of a Pixel Array Detector for Coherent X-Ray Imaging at the Linac Coherent Light Source (LCLS)

Lucas Koerner
Ljk29@cornell.edu
Hugh T. Philipp, Marianne S. Hromalik, Mark W. Tate, Sol M. Gruner



Gruner Biophysics Group – Cornell University

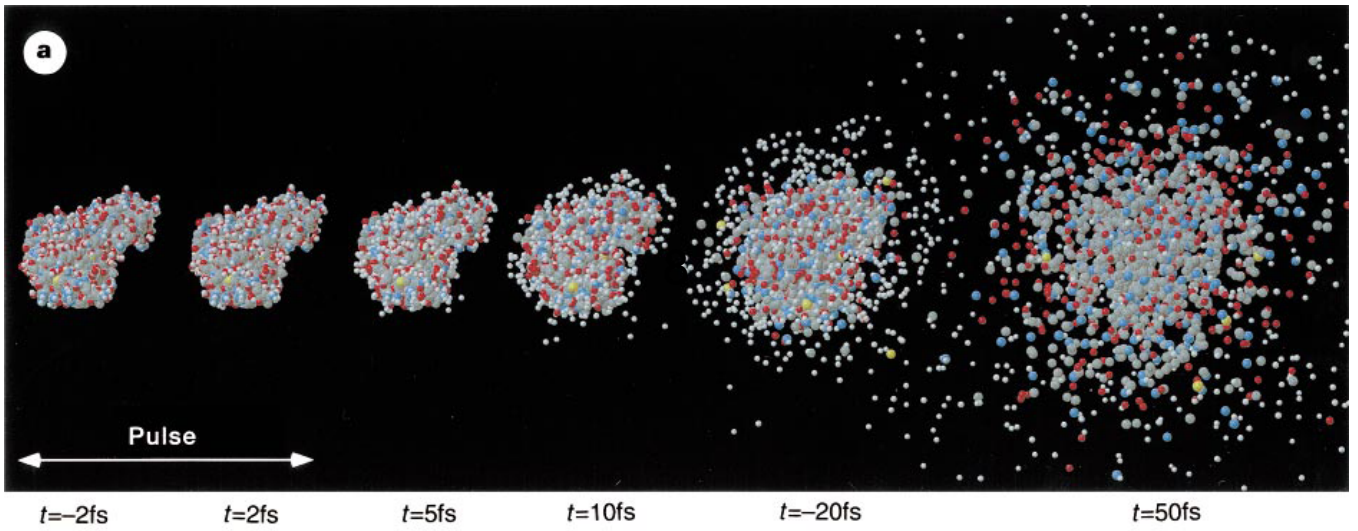
Pixel Conf. 2008 – Sept 24, 2008

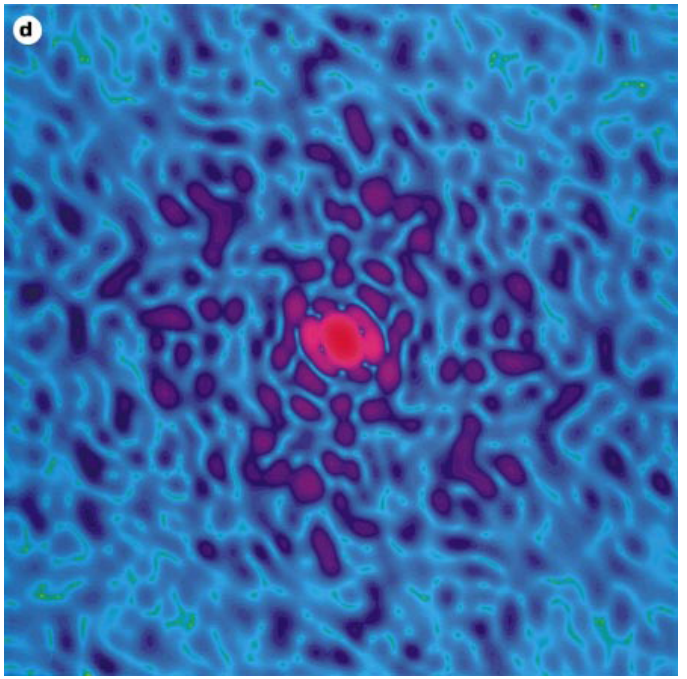
Outline

- Coherent imaging experiment at LCLS
- Desired detector characteristics
- Detector approach
- X-ray tests of single ASIC detectors
  - Noise
  - Linearity
  - Spatial response
  - Radiation robustness

Coherent Imaging Experiment

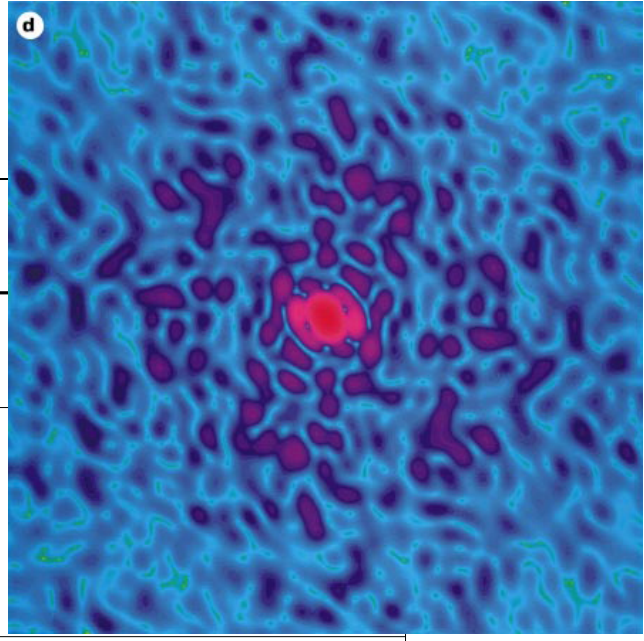
- X-ray Free-Electron Laser (XFEL) at LCLS:
  - Short pulses (femtoseconds)
  - Bright (1e12 photons/pulse)





R. Neutze, et al. Nature vol 406, pp 752-757 (2000).

Detector Requirements

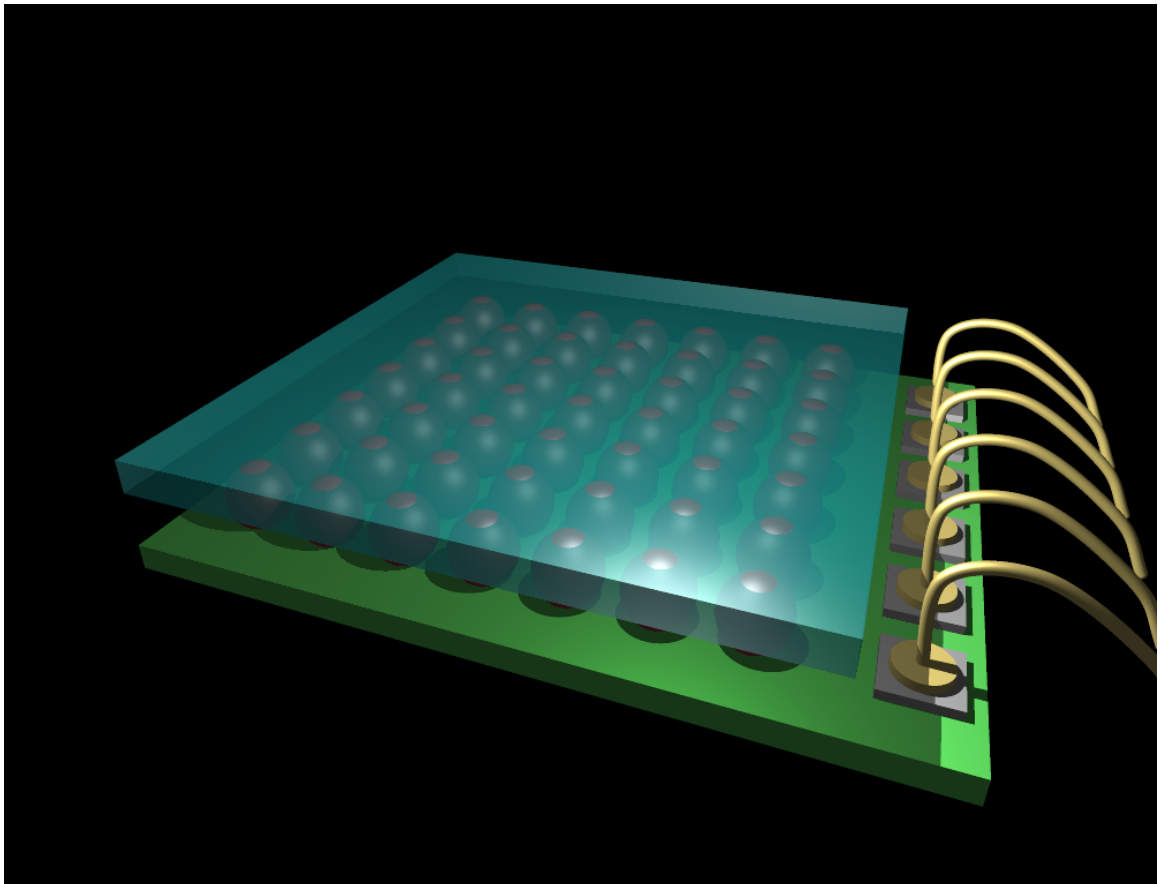


Framing Rate	120 Hz
Pixel Saturation Value	≈1,000 (8 keV)
Read Noise (RMS)	< 0.33 (8 keV); < 730 e- ENC
Instantaneous Hit Rate	1e17 photons/sec/pix
Detector Format	> 500x500 pixels
Pixel Size	~ 100 microns
Detector Area	> 50 mm x 50 mm
Quantum Efficiency (at 8 keV)	> 90%
Point-Spread Function	< 1% to neighbor, < 0.1 % to next neighbor
Radiation Tolerance	65 Mrad (Si) at Detector Face

Hybrid pixel detector (pixel array detector):

Two layers:

* Fully depleted Si detector (500 μm) thick n-substrate, 5-10 kOhm-cm (*SINTEF*)
* Connecting bump-bonds (*RTI*)
* ASIC readout (0.25 micron CMOS - *TSMC*)



Framing Rate	120 Hz
Pixel Saturation Value	≈1,000 (8 keV)
Read Noise (RMS)	< 0.33 (8 keV); < 730 e- ENC

Flexibility of Mixed-Mode CMOS:

* Per pixel programmable gain
* A-to-D in each pixel
* FPGA readout & control

Instantaneous Hit Rate	1e17 photons/sec/pix

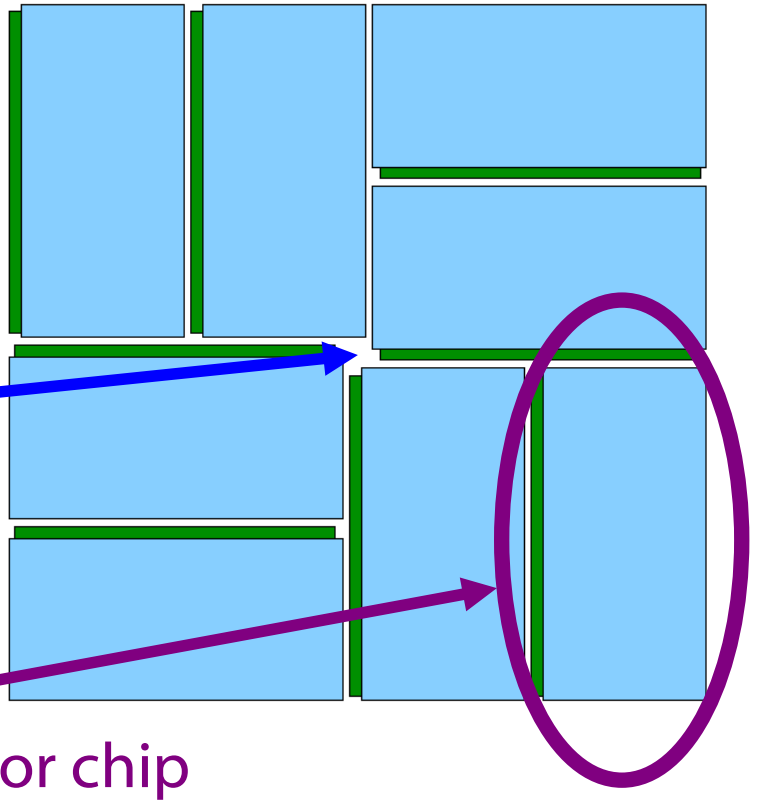
Charge Integrating not Photon Counting

* 500 microns Si stops 99.9%
* Spread in over-depleted sensor set by diffusion during drift (RMS 8.1 microns)

Quantum Efficiency (at 8 keV)	>90% desired. >99% expected
Point-Spread Function	< 1% to neighbor, < 0.1 % to next neighbor
Radiation Tolerance	65 Mrad (Si) at Detector Face

* 16 ASICs, 8 detector chips
  185x194 pixels per ASIC
  total of 758x758 pixels

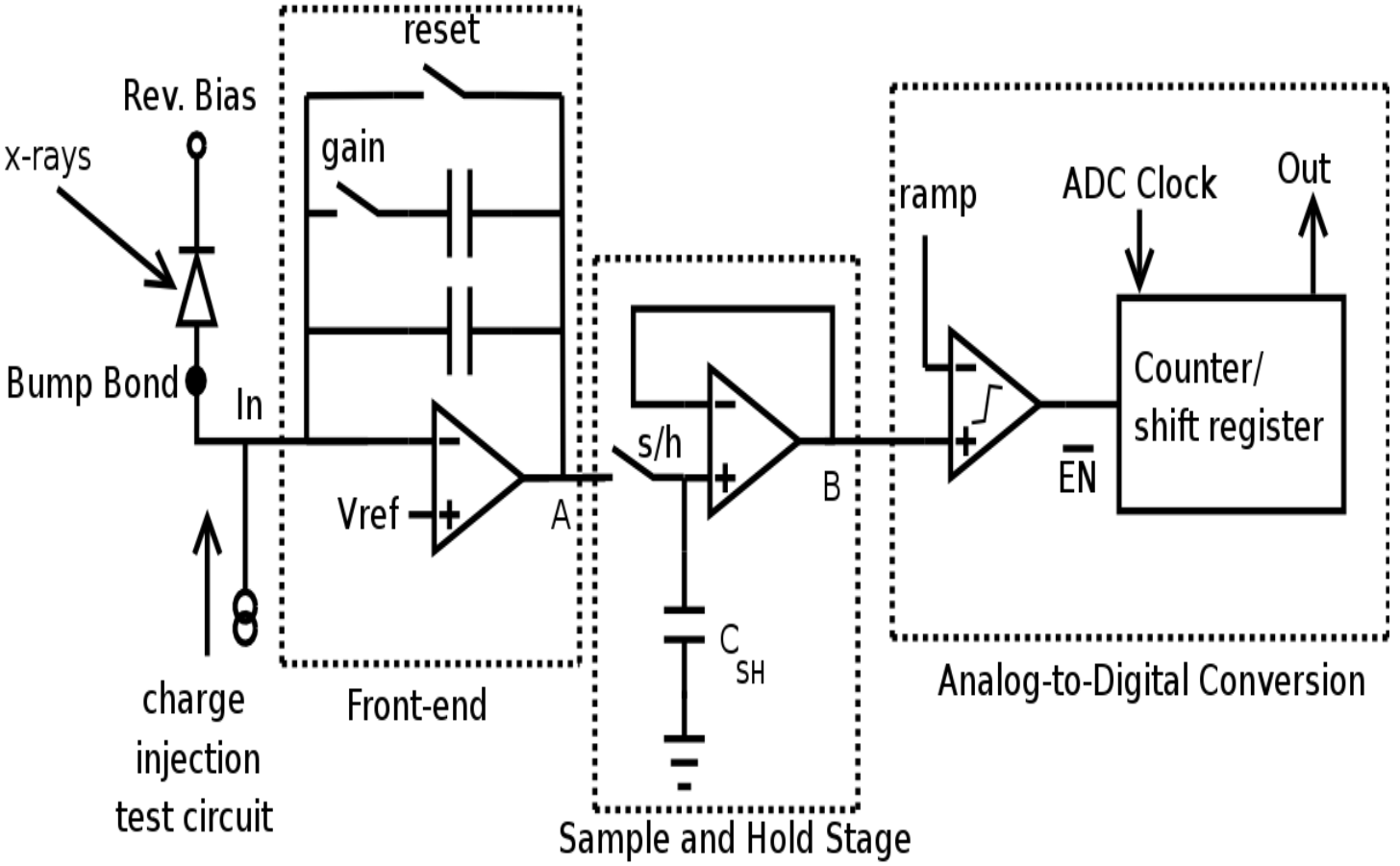
* Central Hole
  for direct beam



38 nm virus to resolution of 0.3 nm
(oversample by x2)
=> 500 pixels

Detector Format	758x758 pixels
Pixel Size	110 microns x 110 microns
Detector Area	83 mm x 83 mm

Pixel Schematic



0.25 µm CMOS

110 x 110 µm pixel

75 fF: High-gain
565 fF: Low-gain

5 µs integration window

14-bit conversion

FPGA Control and Acquisition

For single ASIC testing:

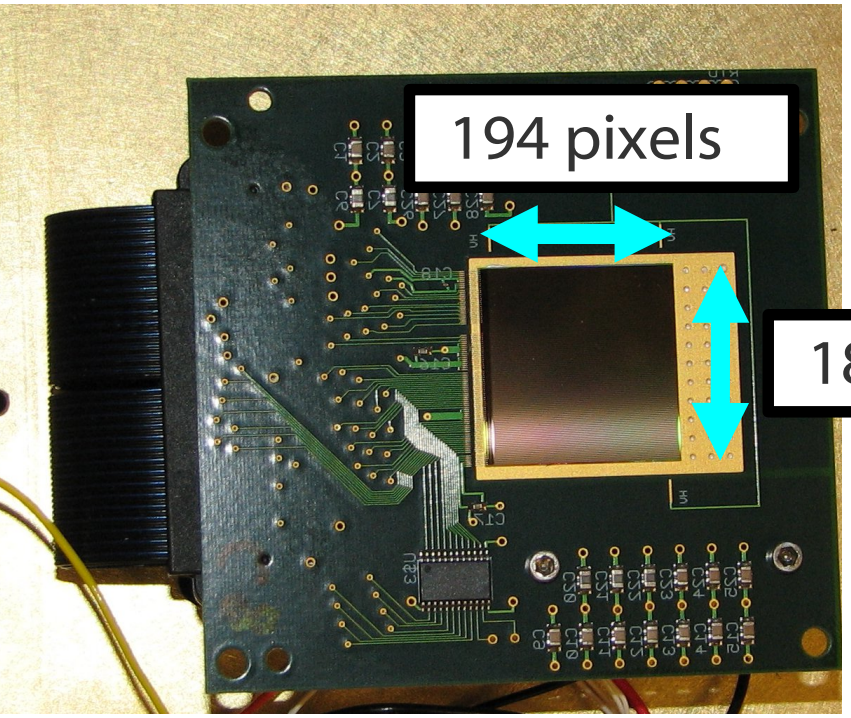
* Xilinx Virtex 4 – XCV100FX.
* Communicates across PCIexpress bus.
* Handles configuration
* Sends control signals during integration and readout
* Control and Acquisition work separately and in parallel
* Data from the detector buffered into FPGA block RAM and sent across PCIe bus (DMA)

16 ASIC detector:

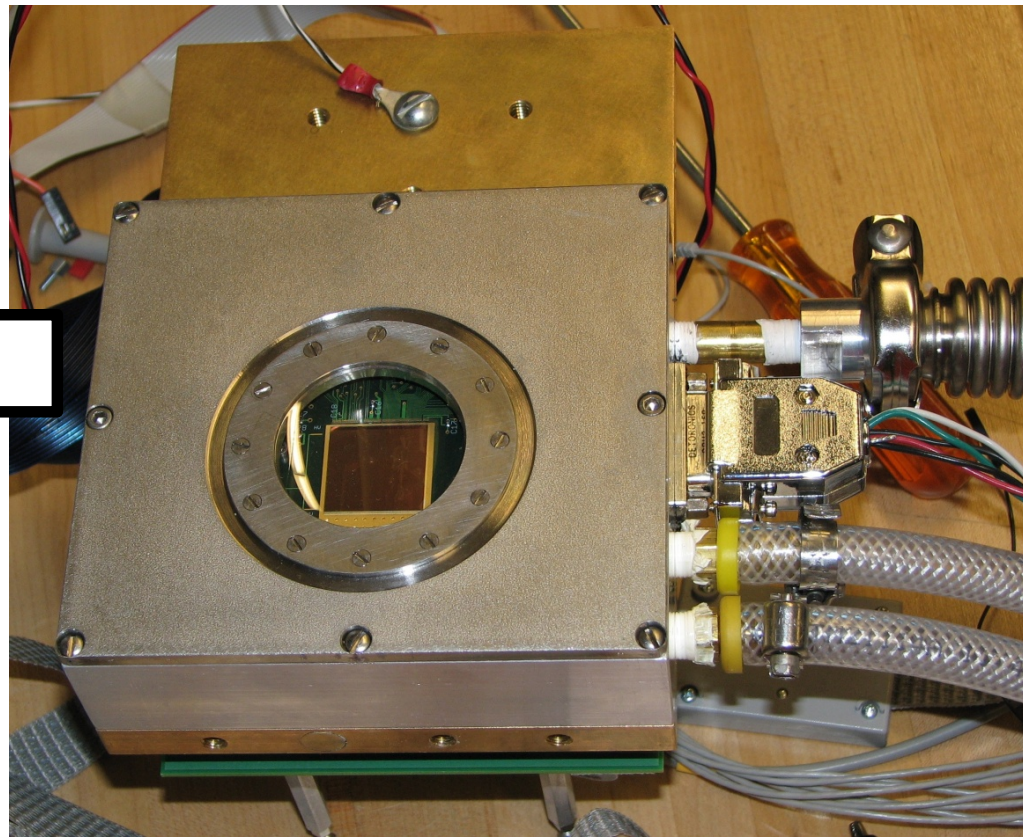
* (1 Gb/s) – FPGA uses Scatter/Gather DMA to PC RAM
* Requires custom disk-controller with continuous rates of 150 MB/s

Marianne Hromalik, Hugh T. Philipp, Lucas Koerner, Mark W. Tate and Sol M. Gruner IEEE NSSC, 2007 3 : 1744-1750.

Single-Chip Testing

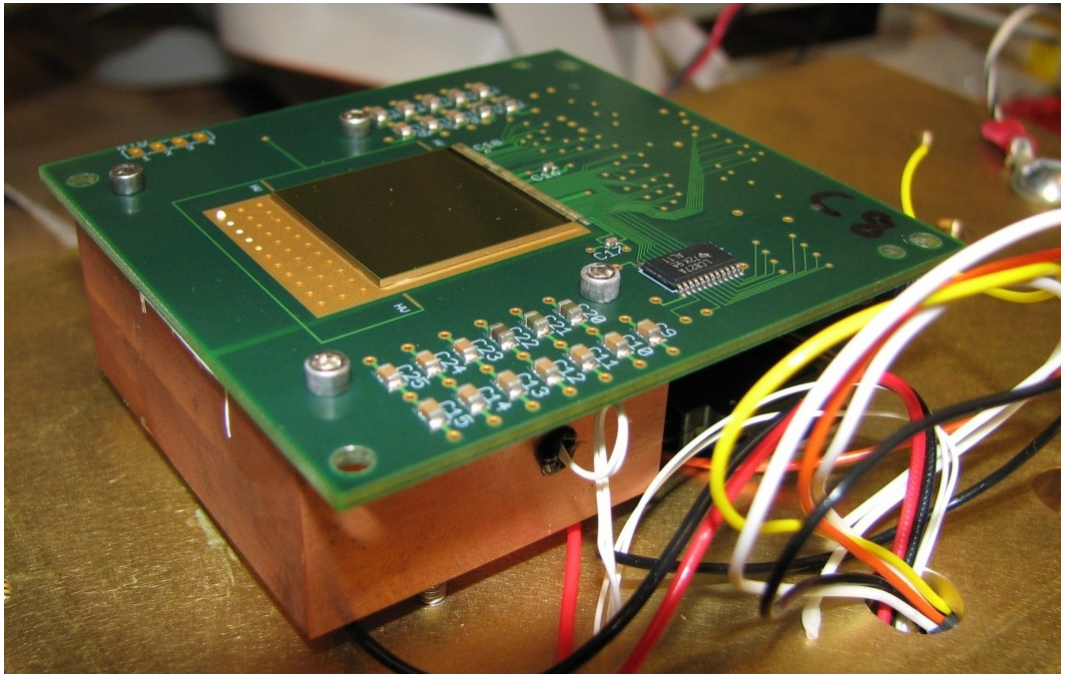


21 mm x 21 mm chip ASIC mounted on a daughter-card



Detector vacuum cryostat: Thermoelectric cooling to -30 °C

Single-Chip Hybrids



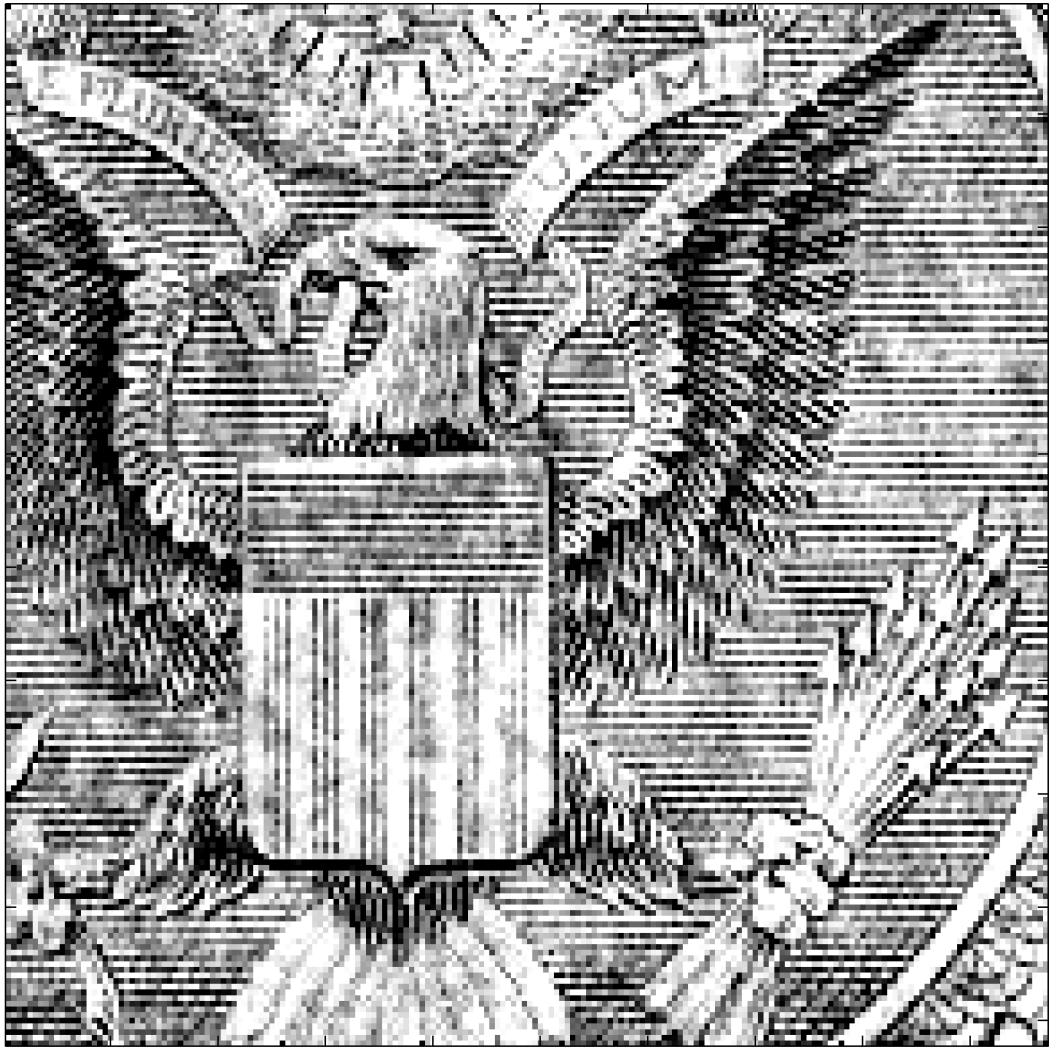
Bump-Bonding (RTI):
18 hybrids tested

Median-connectivity:
0.99987 (5 unconnected)
Mean-connectivity:
0.99891
(one hybrid 0.987)

Dark Current:
40 fA/pix (-14 °C)
0.33 nA/cm^2

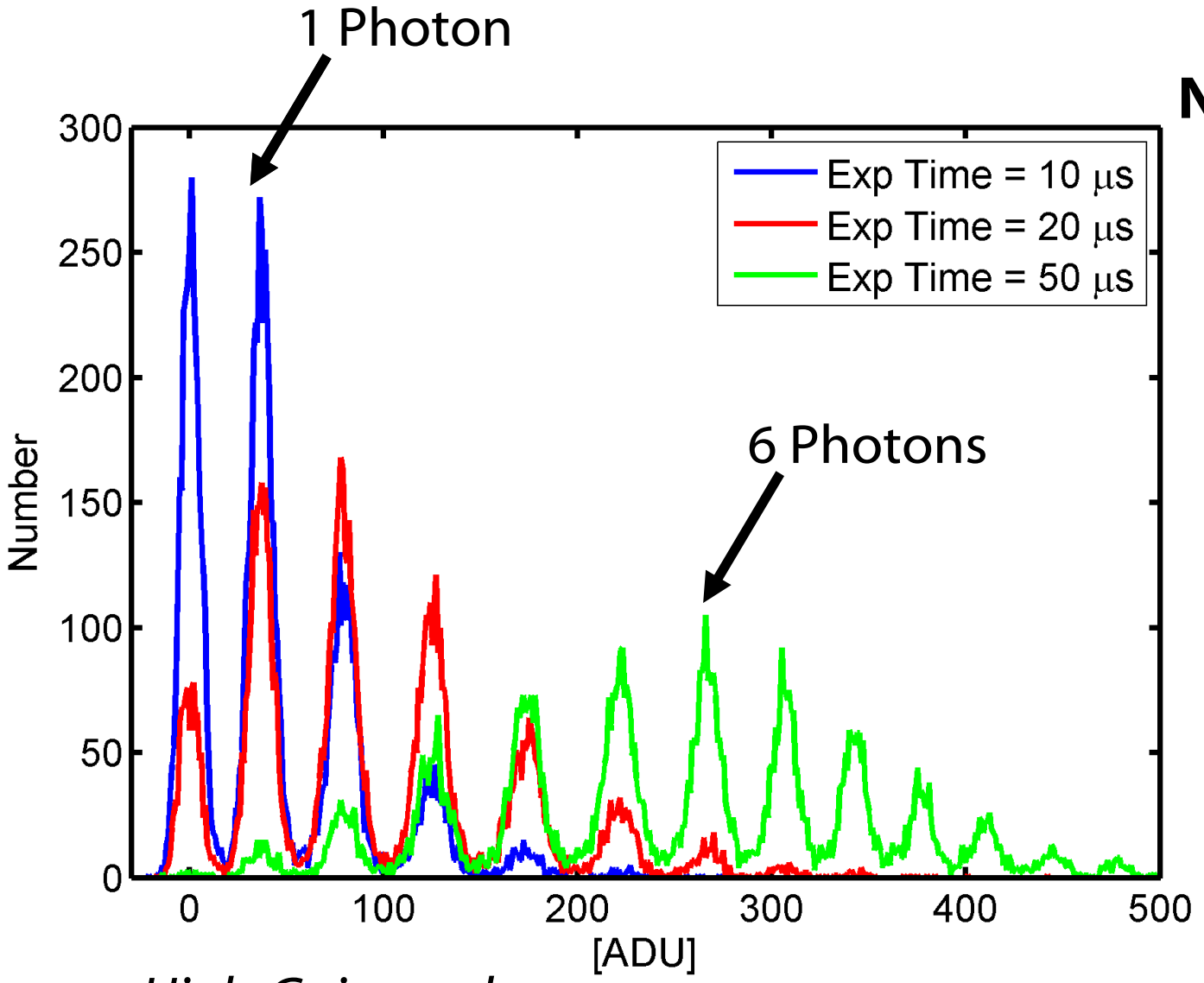
700 fA/pix (18 °C) ⟶ 5 μs integration window: 21 e-
6.4 nA/cm^2

X-Radiograph of $1 Bill



* Taken using Cu K radiation (8 keV)
* Average of eighty 1.4 second exposures
* 10% contrast from dark to light

Single Pixel Response Histogram



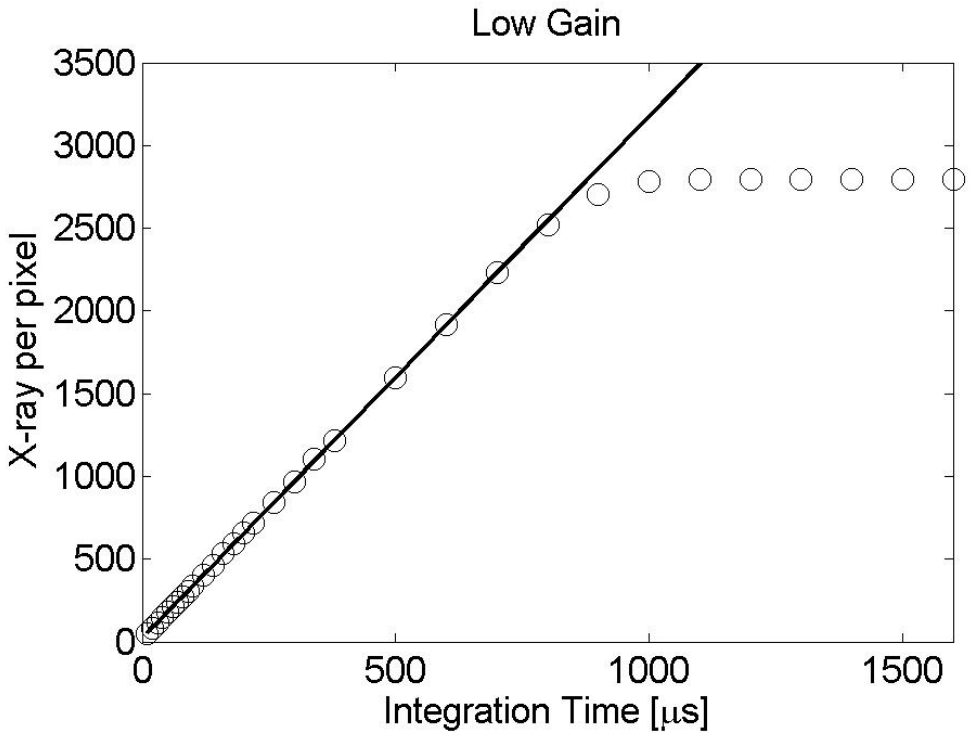
Noise Characteristics:

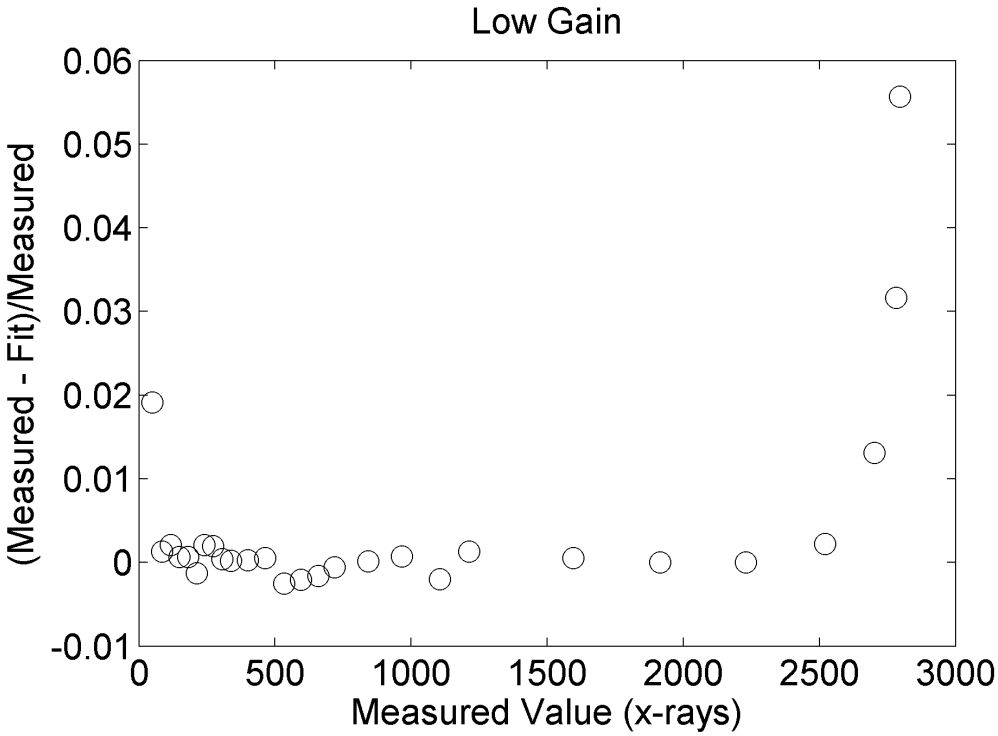
High-Gain:
0.15 x-rays RMS
350 e- RMS
2.8 keV FWHM

Low-Gain:
0.46 x-rays RMS
1000 e- RMS

High-Gain mode
8 keV radiation
Single pixel exposed through 25 μm diameter pinhole

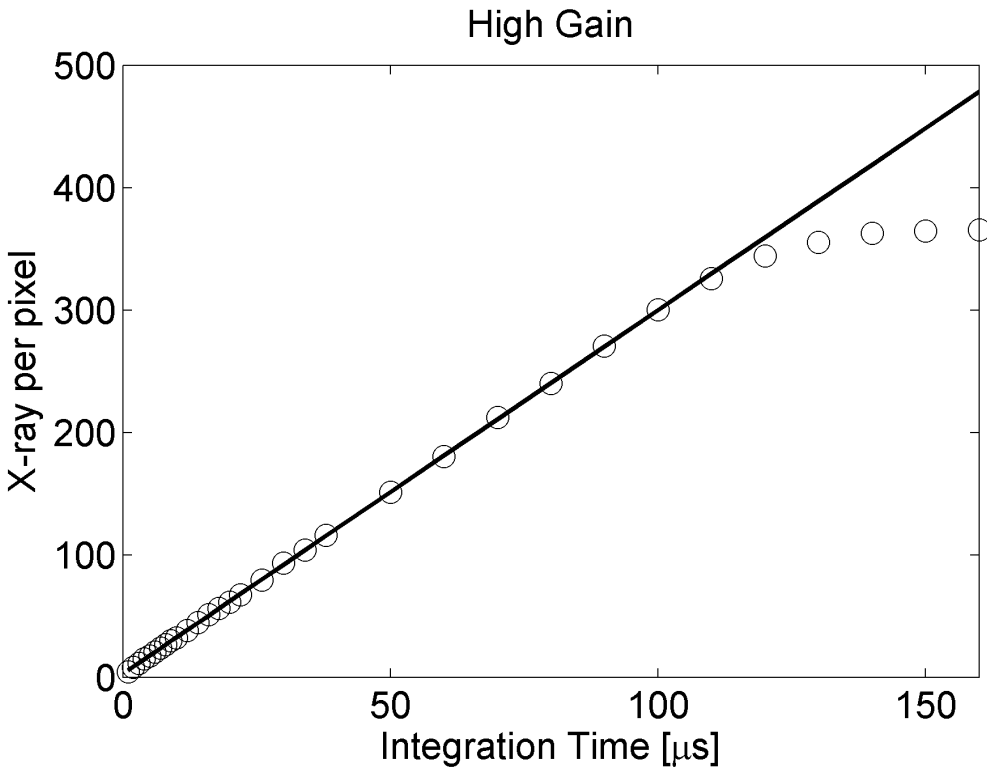
Well-Depth and Linearity

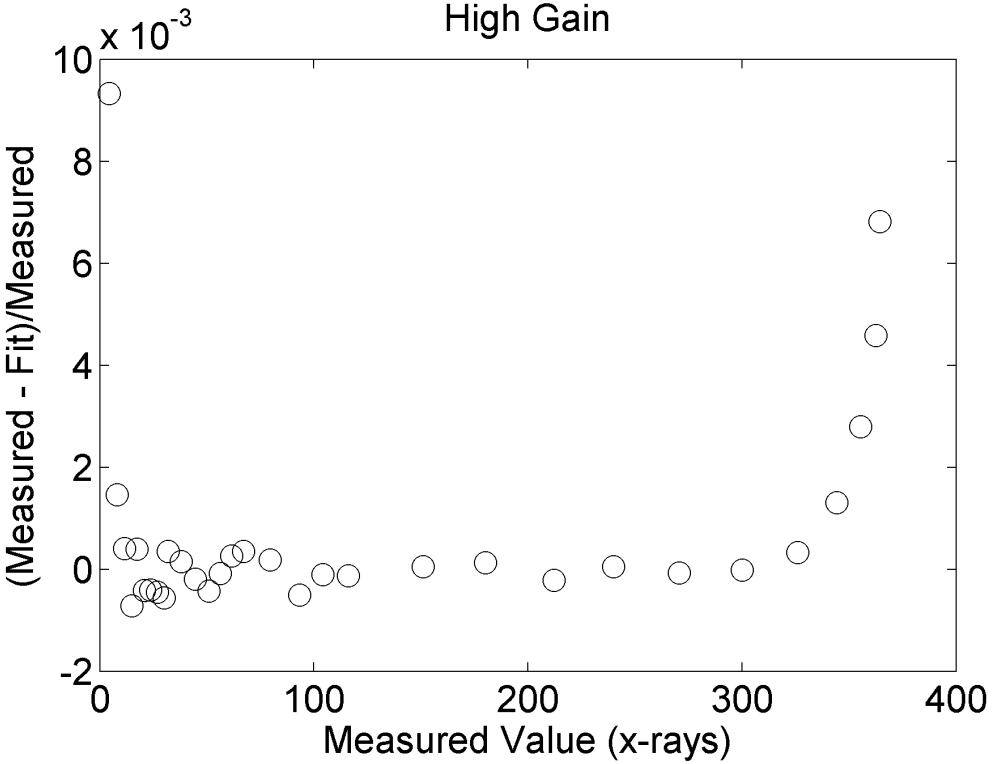




0.35 fC/x-ray and 556 fF => 630 μV/x-ray gain.
3.3 V supply, 2 V front-end swing => ~3000 x-ray full-well
6.6 M electrons
0.15 X-ray read-noise => DR = 20,000 or 86 dB

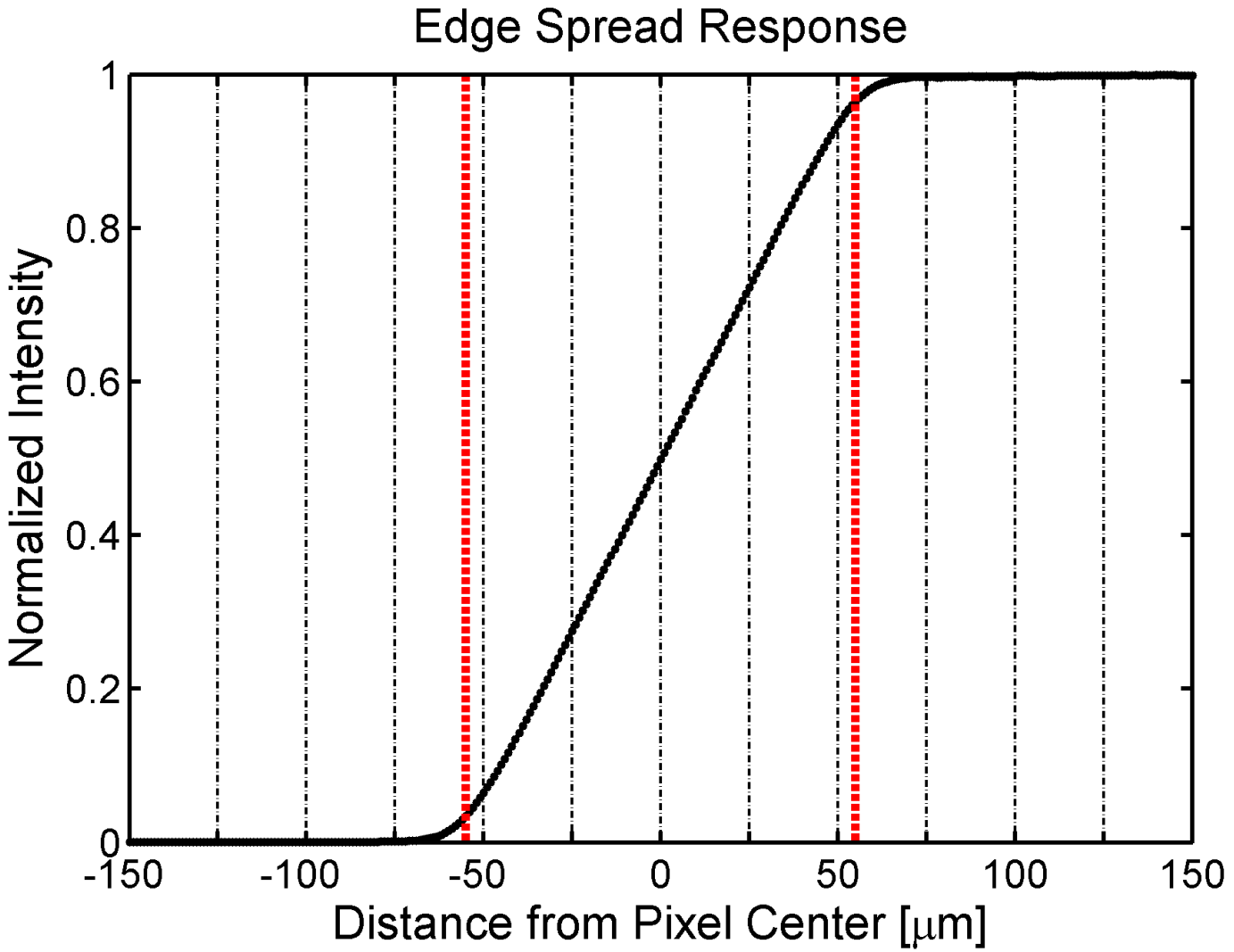
Well-Depth and Linearity





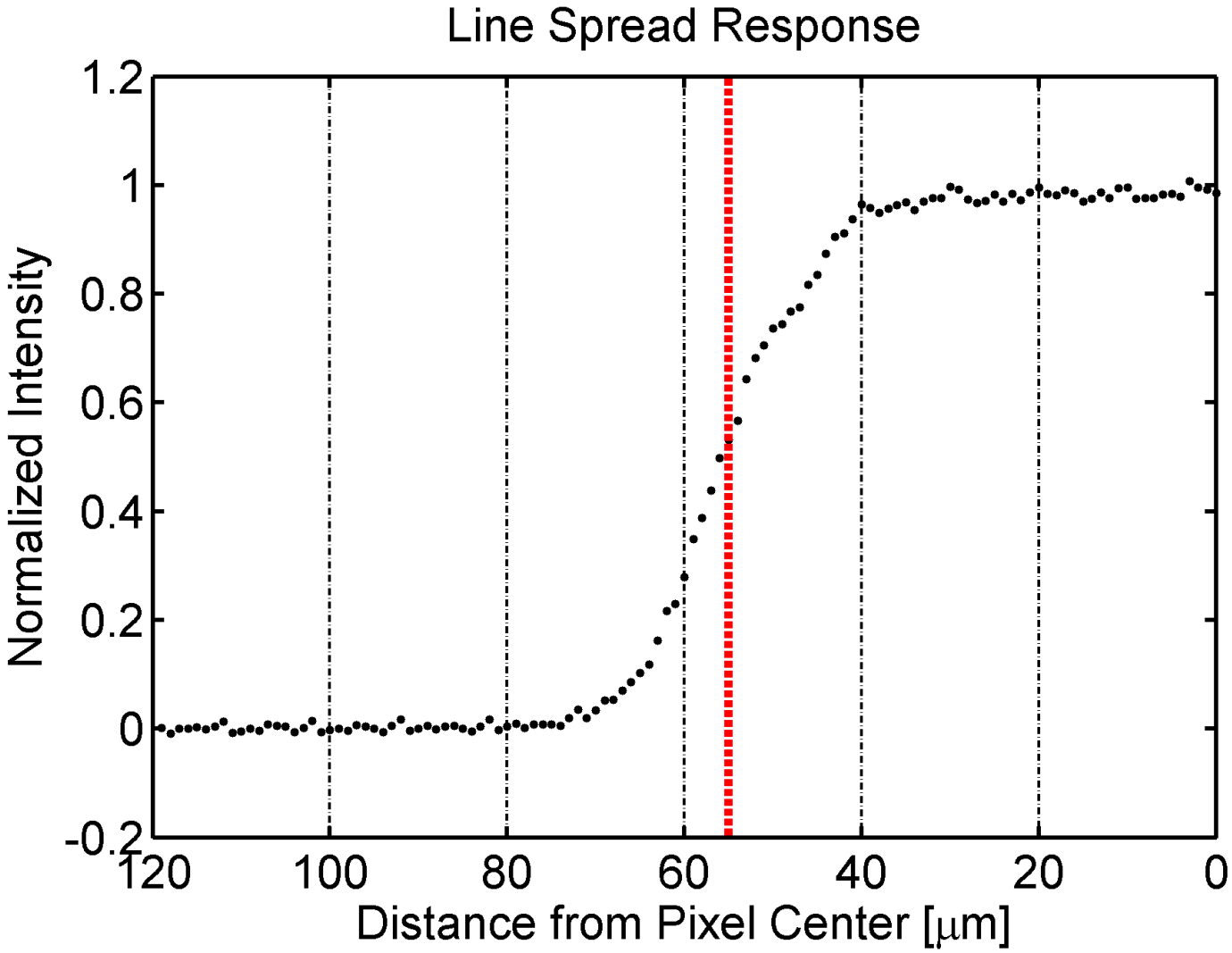
0.35 fC/x-ray and 75 fF => 4.7 mV/x-ray gain.
3.3 V supply, 2 V front-end swing => ~400 x-ray full-well
0.9 M electrons

Spatial Response



* Measured using knife-edge (inclined slightly from detector axis)
* Combined with translation in few micron steps
* Red-lines denote pixel boundary

Spatial Response



* Gradient of edge-spread gives line-spread
* Spreading to 5% level extends to 15 μm past pixel border

Radiation Robustness

Bare ASICs dosed to 400 kRad (Si) [electrically biased at 12 °C]:

* CMOS readout showed problems at levels of 140 kRad (Si)

Annealing:

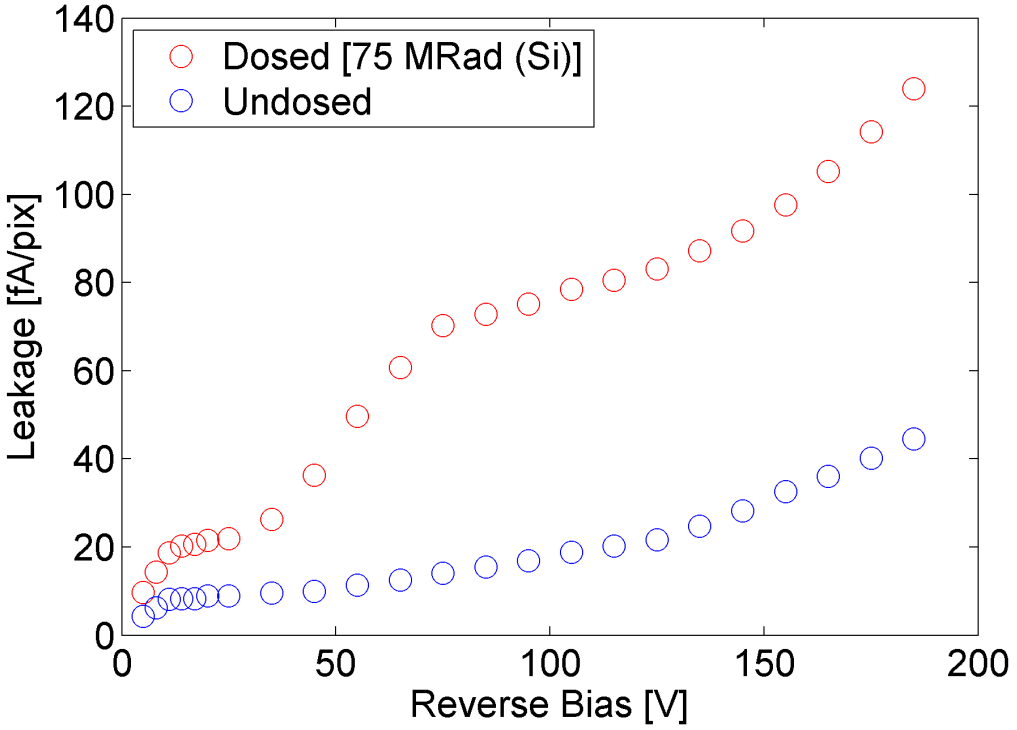
* room temperature anneals (40 days unbiased)
  - almost all effects vanish
* 56 °C one-day anneal removed all residual signs of damage

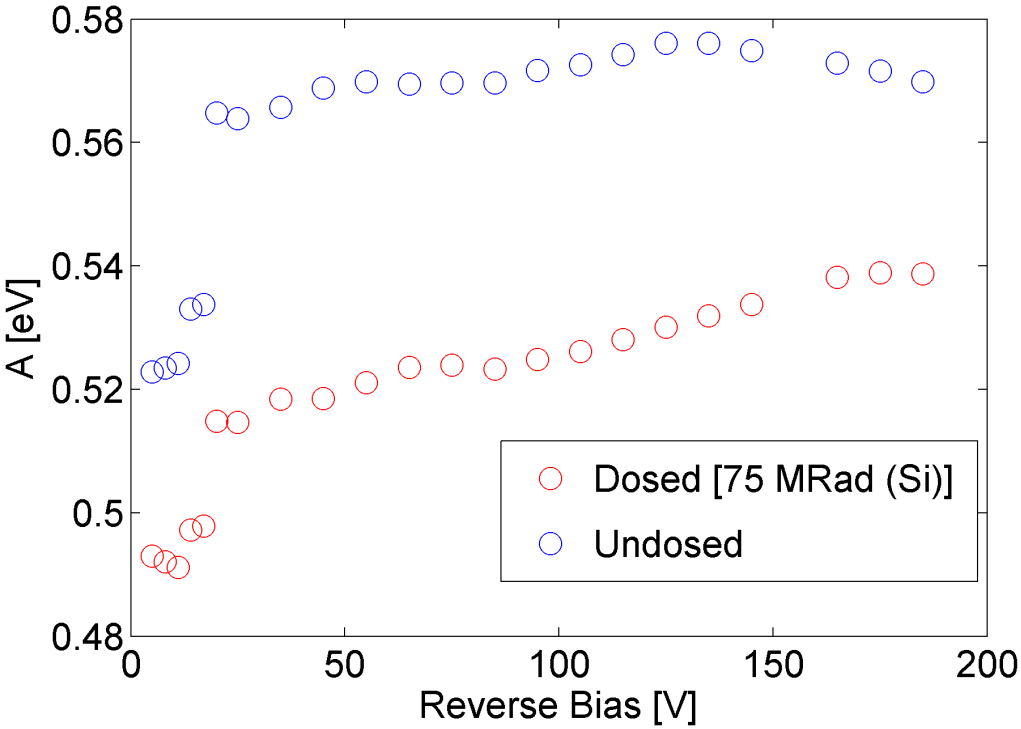
Damage and annealing suggest hole-trapping, possibly activating parasitic transistors through the field-oxide

Hybrids dosed to 75 Mrad (Si):

leakage currents increased, CMOS readout showed few signs of damage

Detector Leakage





* T = -14 ºC
(same I-V scan at nine temperatures)

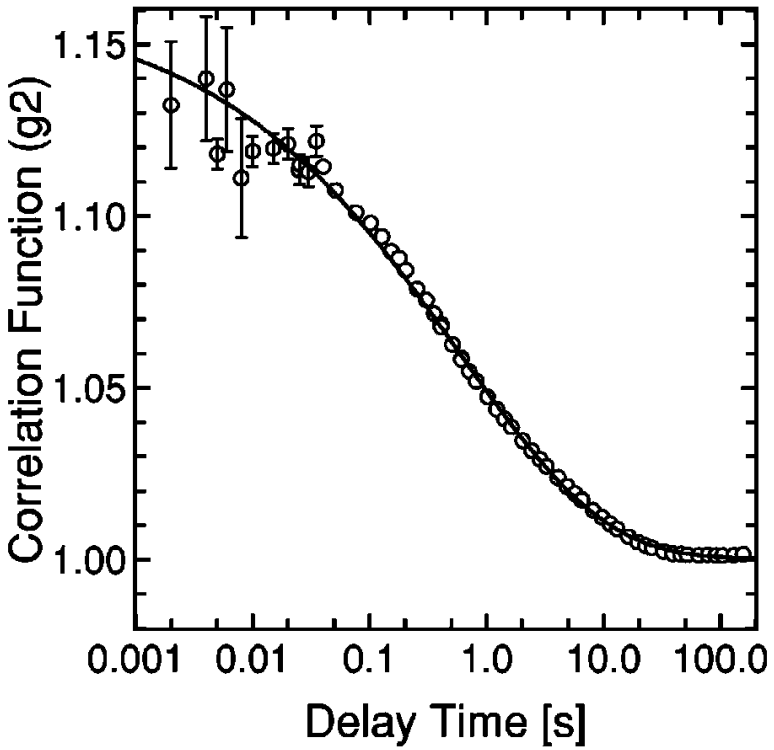
* 65 kRad (Si) at pixel electrodes

$$I \propto e^{(-A/kT)}$$

slope: $\log(I)\ vs.\ 1/kT$

$$E_g(Si) = 1.12\,eV$$

X-ray Photon Correlation Spectroscopy



Falus, Borthwick, Mochrie, RSI (2004) **75**, 4383-4400.

Minimum correlation time: 2 ms
Limited by detector read-out time.

- X-Ray photon correlation spectroscopy is used to study complex dynamics at the nanometer scale.

- How do the nanoscale interactions produce the macroscopic properties we observe?

- Systems of interest include:
  polymer creeping
  protein folding

- Nanoscale systems move ***faster*** than millisecond time scales!

Summary

- Integrating pixel-array detector being developed for LCLS
- 2 cm x 2 cm (194x185 pixels) detectors tested:
  - ENC of 350 e-
  - Full-well up to 6.6 M e-
  - Charge sharing region of 15 microns
  - Frame-rates of 8 ms
  - Excellent bump-bonding results

Acknowledgements

- Cornell LCLS team:

  Hugh Philipp, Marianne Hromalik, Mark Tate, Sol Gruner
- Other Cornell Detector members:

  Current: Darol Chamberlain, Kate Green,

  Former: Daniel Schuette, Alper Ercan
- Stanford/SLAC/LCLS
- Funding: DOE-BES, DOE-BER
- RTI
- SINTEF
- MOSIS

END